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INFLUENCE OF BASE MAT / FLOOR FLEXIBILITY ON EARTHQUAKE RESPONSE OF A BWR-TYPE NUCLEAR REACTOR BUILDING

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SUMMARY

Effects of an analysis modeling of BWR-type nuclear reactor buildings on earthquake response analysis are discussed. First, general structural characteristics of the buildings are reviewed, and it is pointed out that the depth of each floor is small compared with the wall thickness. Second, an earthquake response analysis is conducted for a prototypical ABWR-type building, and the results are compared for base mat flexibility considered and neglected. Large effects of base mat flexibility are observed for vertical base mat displacement and reaction stress distribution of the supporting rock. Some effects are also observed on stress distribution in the building walls. Effects of floor in plane flexibility are observed as the difference between transfer functions, maximum acceleration distributions and floor response spectra for the outer and center points on the same floor.

INTRODUCTION

An earthquake response analysis of a reactor building is used not only for aseismic design of the building structure itself but also for aseismic design of internals, pipings and machines, which cover a wide range of natural frequencies. The analytical model of the building should therefore express the dynamic characteristics of the building over a wide frequency range. The structural characteristics of a typical A-BWR-type nuclear reactor building, as an example, are reviewed and idealized into a Finite Element Method Model. To clarify the effects of the flexibility of the base mat and floors on earthquake response of the reactor building, earthquake response analyses are conducted with the two models: Case-1, which takes into account the flexibility of the base mat, and Case-2, which neglects the flexibility of the base mat. For both models, two site supporting layers are considered for the shear wave velocity (Vs) : (1) hard rock with Vs = 1000 m/sec and (2) soft rock with Vs = 500 m/sec.

The analytical results are compared between Case-1 and Case-2, and the effects of the flexibility of the base mat and floors on earthquake response of the reactor building are discussed focusing on the following points : (1) transfer function from control point to building reference points, (2) stress distribution of seismic forces of shell wall and outer wall, (3) floor response spectra on building reference points and (4) reaction stress distribution of the supporting rock just under the base mat.

STRUCTURAL CHARACTERISTICS OF AN A-BWR TYPE REACTOR BUILDING

At present, the main structures of nuclear related facilities in Japan are seismically designed as rigid structures. A typical Advanced type Boiling Water Reactor (A-BWR) building is shown as an example in Fig. 1. A containment vessel and shielding wall are combined as a Reinforced Concrete Containment Vessel (RCCV) and is erected at the center of the building plan. The RCCV is one of the main aseismic elements. Machines and pipings are installed outside the shell wall and a rectangular outer wall covers the space. The outer wall is the

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another main aseismic elements. Reactor buildings constructed in high seismic zones sometimes have double outer walls which contain auxiliary facilities and diesel generators to protect against base mat uplift by lateral seismic forces. These seismic elements are erected on a base mat. The geometries of the structure depend on its capacity and seismic design force. The typical dimensions and structural characteristics of a recent 1,300 MWe class ABWR building are shown in Table 1.

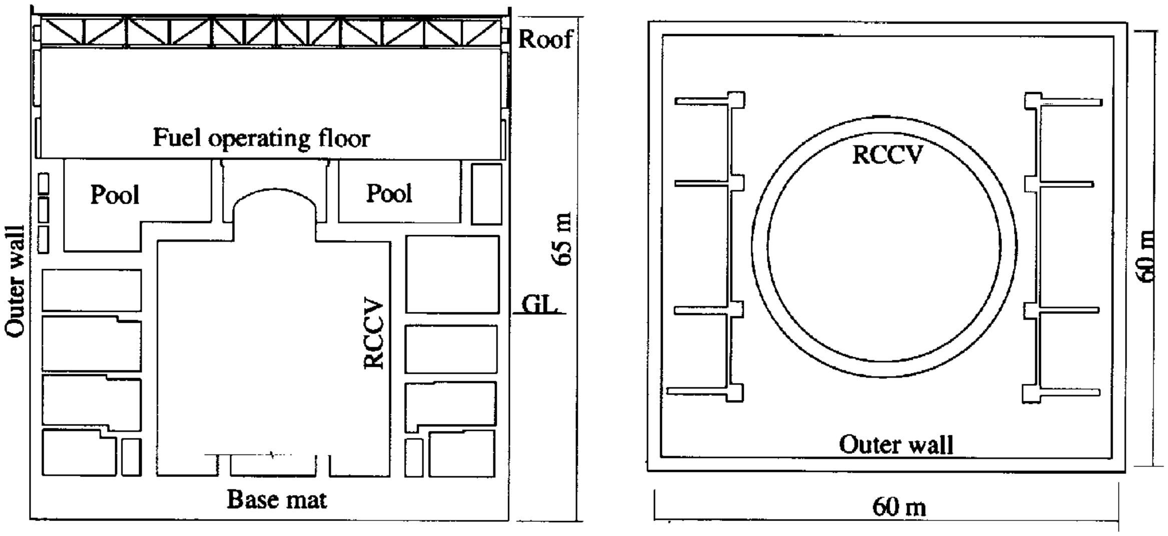
Table 1: Prototypical dimensions of recent ABWR building

Shell wall thickness	(Shielding demand)	2 m
Outer wall thickness	(Just beneath operating floor)	1.0 m ~ 1.2 m
	(Base mat top)	1.8 m ~ 2.0 m
Pool wall depth		2.0 m ~ 2.3m
Slab thickness		0.5 m ~ 0.8 m
Base mat plan		60 m ~ 80 m square
Base mat thickness		6 m ~ 8 m
Total height		65 m ~ 75 m
Pool wall height		8.2 m ~ 13.6 m

Structural characteristics of the reactor building are summarized as follows :
(1) Slab thickness is small compared with wall depth.
(2) Base mat thickness is about 10 % of its width.
(3) Total outline is nearly cubic.
(4) Pool wall connects with shell wall top and outer wall.

As discussed before, the main aseismic elements of a reactor building are the shell wall and the outer wall. The shell wall is located near the center of the building while the outer wall is located far from the center. The displacement for lateral seismic force of each element consists of "shear displacement" and "flexual+rocking displacement". The flexural+rocking component is predominant for shell wall displacement while the shear component is predominant for outer wall displacement. The displacement of the shell wall is small at lower levels, and the increment increases with the height, while the displacement of outer wall is large at lower levels and the increment decreases with the height. These structural characteristics for lateral seismic force between shell wall and outer wall are summarized in Table 2.

These aseismic elements with different displacement characteristics are erected on the base mat and connected by relatively thin slabs at each floor. Therefore, it is expected that the difference in displacement characteristics of each seismic element causes an irregular distribution of the base mat displacement and the rotational angle at the shell wall base differs from that of the outer wall base. Furthermore, this difference in rotational angles will cause complicated reaction stress distributions between the base mat bottom and the supporting soil. However, the flexibility of each floor slab and base mat is sometimes neglected for simplicity in mathematical models of earthquake response analysis as shown in Fig. 2. This paper discusses the effects of this flexibility on the earthquake response.



(a) Section (b) Plan of base mat top

Figure 1 : Prototypical advanced type boiler water reactor building

Table 2: Comparison of displacement characteristics between shell wall and outer wall (Expression means relation between shell wall and outer wall)

Aseismic element		Shell wall	Outer wall
Location in plan		Near the center	Far from the center
Predominant displacement component	Shear	Flexural + rocking	
Displacement increment	(Low level)	Small	Large
ratio to height	(High level)	Large	Small

EARTHQUAKE RESPONSE ANALYSIS

Analytical model of the building

The analysis treats a typical ABWR building shown in Fig. 1. It is 60m by 60m in plan, and 63.9m high, and its base mat is 6.0m thick. To reduce calculation time, the building is modeled as symmetrical in both the x-z and y-z planes and its 1/4 portion is idealized by the Finite Element Model as shown in Fig. 3 in which solid elements are used for base mat while shell and beam elements are used for super structure. Reinforcing bars are neglected. The material properties of the concrete are shown in Table 3 and the analysis remains in linear assumption.
The following two models are considered to clarify the effects of base mat flexibility :

F Model : Flexible base mat model
R Model : Rigid base mat model [NUREG, 1987]

The same FEM mesh layout is used for both models. The rigid base mat assumption is realized by applying a large Young's modulus (1,000 times) for the base mat elements.

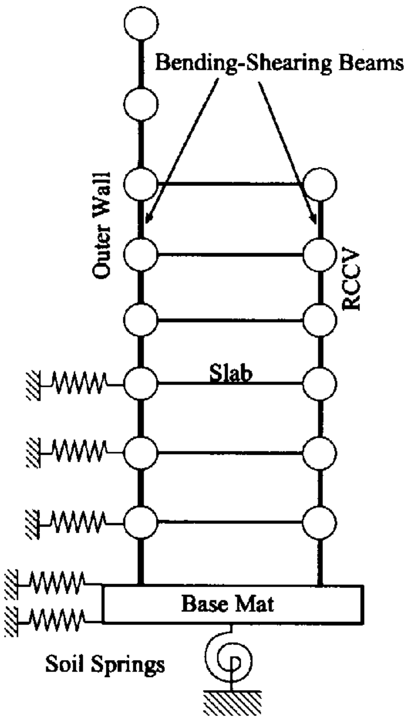


Figure 2 : An example of mathematical model Earthquake response analysis

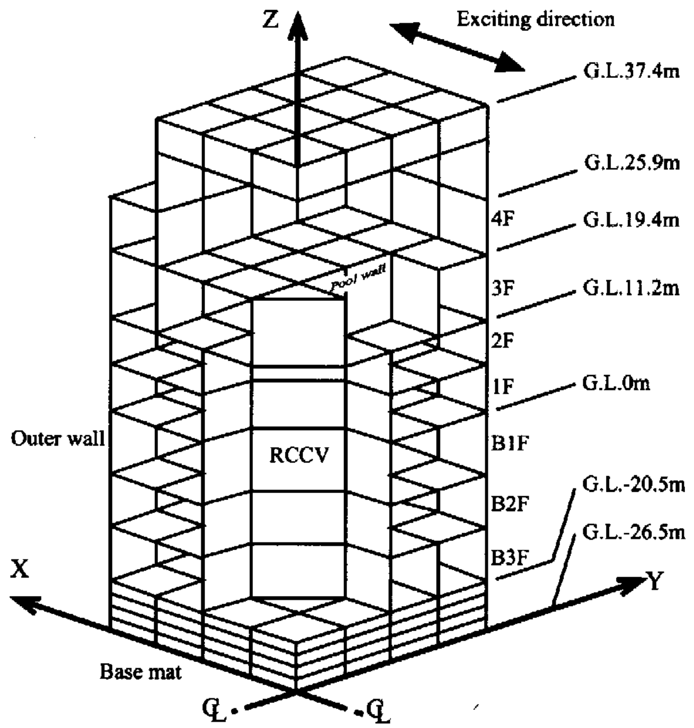


Figure 3 : Mesh layout for finite element model

Table 3: Material properties of concrete

Young's modulus	Shear modulus	Poisson's ratio
tonf/cm2	tonf/cm2	
270.0	115.7	1/6

Soil conditions

The soil properties and soil profile are shown in Fig. 4. Two cases of shear wave velocity of the supporting layer are considered: 500 m/sec (Soft rock) and 1000 m/sec (Hard rock). The surface layer is neglected. Soil-structure interaction effects are evaluated by Thin Layer Method which is based on wave propagation theory for semi-infinite elastic media.

Input motion

An artificial earthquake motion [MITI, 1980] was used for the earthquake response analysis on the outcrop surface of the supporting layer denoted as control point in Fig. 4. Its acceleration time history and response spectrum are shown in Figs. 5 and 6, respectively. The excitation direction is x-direction which is perpendicular to pool wall.

Analysis results

Transfer function

The transfer functions from the control point which is an outcrop surface of the supporting layer as shown in Fig. 4 to the reference points on the 3rd floor are shown in Fig. 7. The peak amplitudes at fundamental frequencies (2.8 Hz for the soft rock site and 3.8 Hz for the hard rock site) at the center point (A) are 8 % and 15 % larger, respectively, than those for the outer point (B). The second peak amplitude (7.8 Hz for the both soft and the hard rock sites) at the center point (A) is twice as large as that for the outer point (B). These phenomena occur because of in-plane deformation of the 3rd floor. However, the base mat flexibility has a slight effect on the transfer functions.

Seismic force distribution of RCCV and outer wall

The effects of base mat flexibility on shear force and overturning moment distribution of the RCCV and the outer wall are shown in Figs. 8~11. The rigid base mat model gives larger results for the RCCV than for the flexible base mat model by 1.2~1.1 times for shear force and 1.3~1.1 times for overturning moment because of the constraining effect of the RCCV by the base mat. Accordingly, the results for the outer wall for the rigid base mat model are smaller than those for the flexible base mat model.

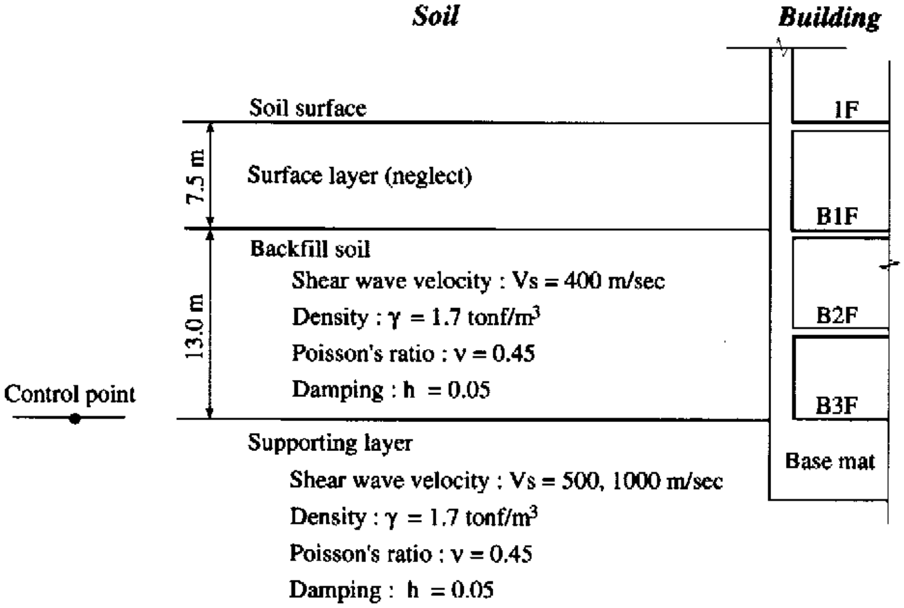


Figure 4 : Soil properties and soil profile

Maximum response acceleration of third floor

The maximum response acceleration patterns for the third floor are shown in Fig. 12, which also shows in-plane deformation of the 3rd floor. The values for the center point are 10 % larger than those for the outer point. The base mat flexibility has a little effect on either of them.

Floor response spectra

Floor response spectra for the center point (A) and the outer point (B) are shown in Fig. 13, which also shows in-plane deformation of the 3rd floor. The peak amplitude, for the fundamental periods (0.36 seconds for the soft rock site and 0.26 seconds for the hard rock site) at the center point (A) are 10 % and 17 % larger, respectively, than those for the outer point (B). The second peak amplitude (0.13 seconds for both the soft and hard rock sites) for the center point (A) is 1.5 times that of the outer point (B). Base mat flexibility also has a little effect on them.

Vertical displacement of base mat bottom

The maximum response vertical displacements of the base mat bottom are shown in Fig. 14. The hatched area is just beneath the RCCV zone. The results for the flexible base mat model show that the rocking angle for the RCCV portion is larger than that for the outer wall portion. As a result, the symmetric axis line (x-axis) is distorted from a straight line, while the outer edge parallel to the exciting direction maintains an almost straight line because of the constraint of the outer wall. These phenomena are common for both soft and hard rock sites.

Vertical reaction stress distribution of base mat bottom

The maximum response vertical reaction stress distributions of the base mat bottom are shown in Fig. 15. The rigid base mat model shows stress concentration only at the base mat corners, while the flexible base mat model shows stress concentration at the base mat corners and also a large stress level at the RCCV bottom. This tendency is clearer for the hard rock site. The overturning moment from the RCCV induces vertical stress on the base mat top and a portion of it is transferred to the supporting layer just beneath the RCCV region and another portion is transferred to the surrounding area outside of the RCCV region through shear force and torsional force in the base mat. The maximum overturning moment from the super structure to the base mat and reaction overturning moment of the supporting layer are summarized in Table 4. The ratios of the reaction overturning moment just beneath the RCCV region to the overturning moment from the RCCV obtained from the flexible base mat model are 0.49 (soft rock site) ~ 0.81 (hard rock site). The rock layers under the base mat have enough stiffness to support directly the large part of the overturning moment from the RCCV. Those obtained from the rigid base mat model are 0.10 (soft rock site) ~ 0.15 (hard rock site). In this case, the rigidity of the base mat is over-estimated and a large part of the overturning moment from the RCCV is transferred to the surrounding area outside the RCCV region. These difference should be taken into account in base mat uplift check.

Table 4: Maximum overturning moment

OTM : Overturning moment

Soil Condition	**Soft Rock Site**			**Hard rock site**		
Flexible Base Mat Model	tonf m	(%)	[Ratio]	tonf m	(%)	[Ratio]
OTM from RCCV	35282	(27)	[1.00]	78680	(28)	[1.00]
OTM from other than RCCV	96153	(73)		205600	(72)	
Total OTM	131435	(100)		284300	(100)	
Reaction OTM just beneath RCCV Region	17277	(13)	[0.49]	63750	(22)	[0.81]
Reaction OTM other than RCCV Region	114158	(87)		220550	(78)	
Rigid Base Mat Model	ton m	(%)	[Ratio]	ton m	(%)	[Ratio]
OTM of RCCV	44848	(35)	[1.00]	87560	(30)	[1.00]
OTM other than RCCV	83590	(65)		203100	(70)	
Total OTM	128400	(100)		290700	(100)	
Reaction OTM just beneath RCCV Region	4670	(4)	[0.10]	12803	(4)	[0.15]
Reaction OTM other than RCCV Region	123730	(96)		277897	(96)	

CONCLUSIONS

The conclusions drawn from the analysis are summarized as follows ;

(1) The base mat shows local bending deformation under the RCCV.

(2) The base mat flexibility affects on the distribution of the shear force and overturning moment between the RCCV and the outer wall .

(3) The reaction stress distribution of the supporting rock under the base mat shows a fairly complicated pattern which depends on the layout of the building's structural components.

(4) The in-plane deformation of the upper floors affects the transfer functions, the maximum response accelerations and the floor response spectra. These results for the center point are larger than those for the outer point.

(5) More rational aseismic design not only for building structure but for internals, pipings and machines can be realized by taking into account the flexibility of the base mat and floors.

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Technical Guidelines for Aseismic Design of Nuclear Power Plants, Translation of Japan Electric Association Guidelines, 4601-1987, NUREG/CR-6241

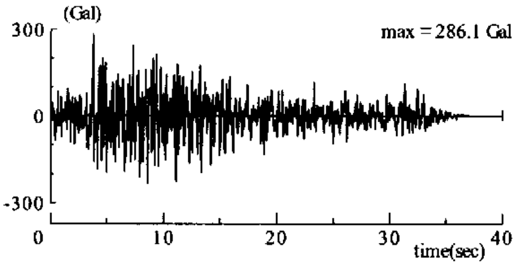


Figure 5: Acceleration time history of input earthquake

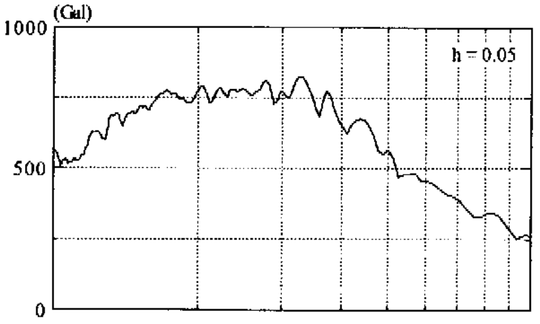
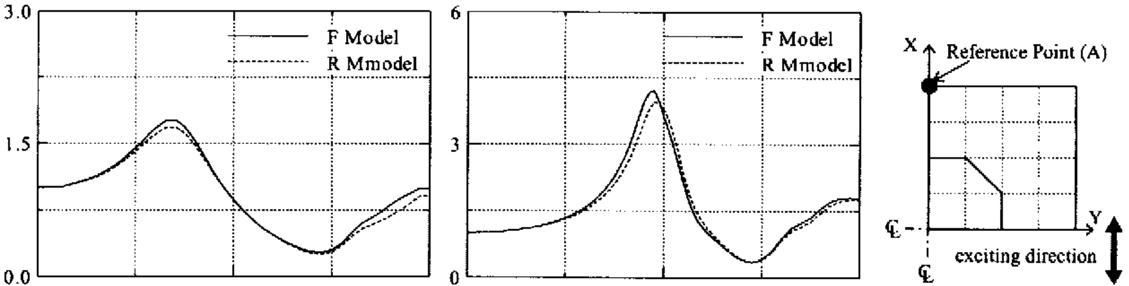
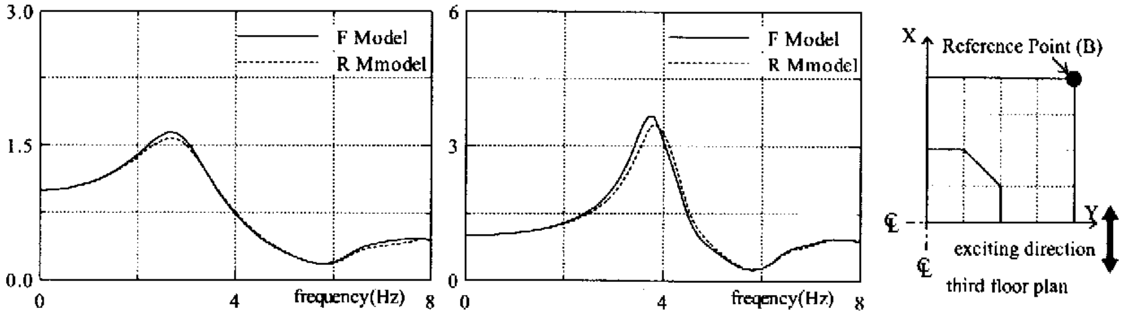


Figure 6: Response spectrum of input earthquake

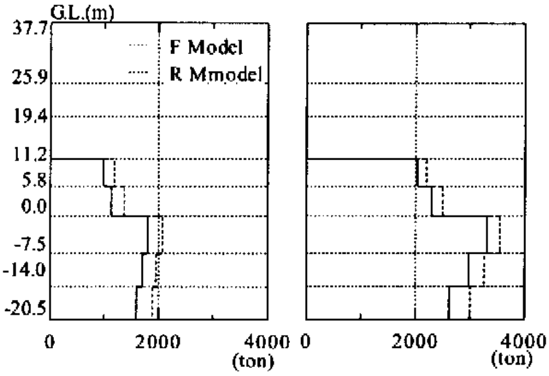


(a) Soft rock site (b) Hard rock site
Reference Point (A)



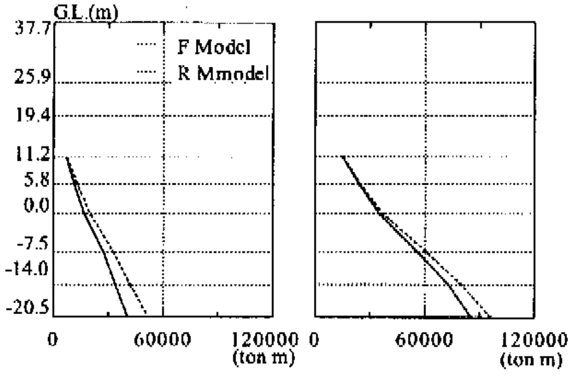
(a) Soft rock site (b) Hard rock site
Reference Point (B)

Figure 7: Transfer function of third floor



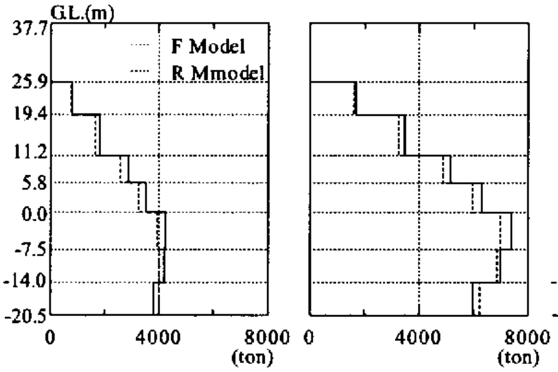
(a) Soft rock site (b) Hard rock site

Figure 8: Maximum response shear force of RCCV



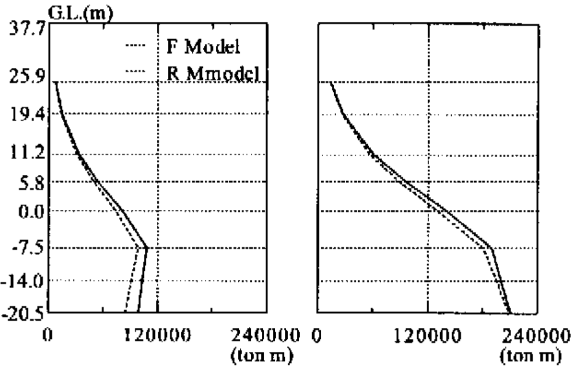
(a) Soft rock site (b) Hard rock site

Figure 10: Maximum response overturning moment of RCCV



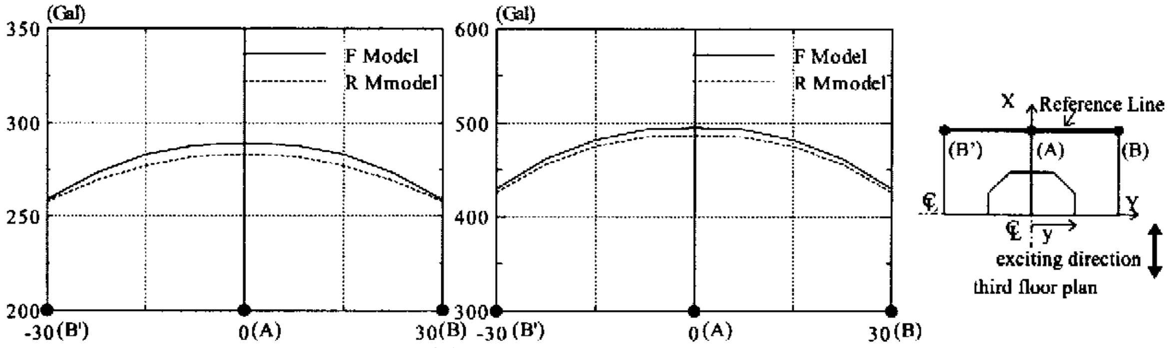
(a) Soft rock site (b) Hard rock site

Figure 9: Maximum response shear force of outer wall



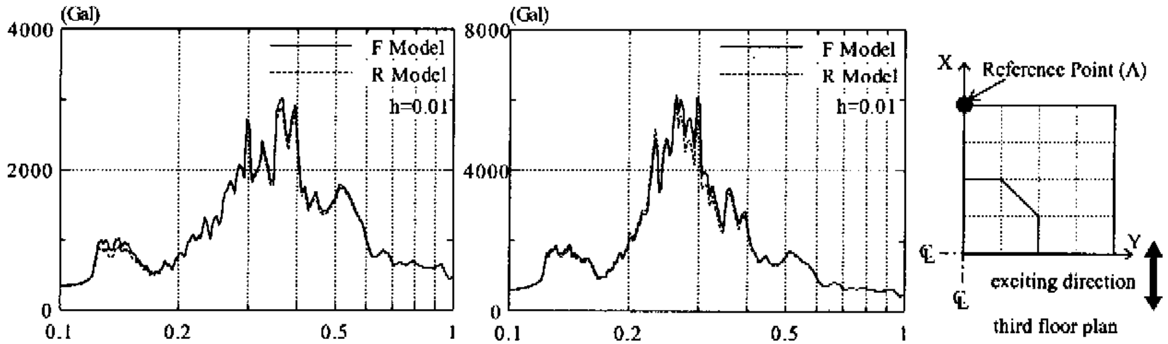
(a) Soft rock site (b) Hard rock site

Figure 11: Maximum response overturning moment of outer wall



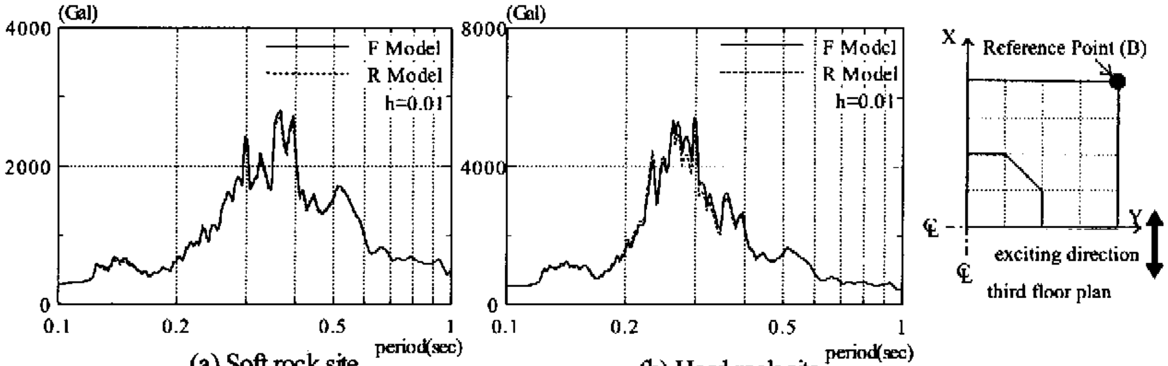
(a) Soft rock site (b) Hard rock site

Figure 12: Maximum response acceleration pattern of third floor



(a) Soft rock site (b) Hard rock site

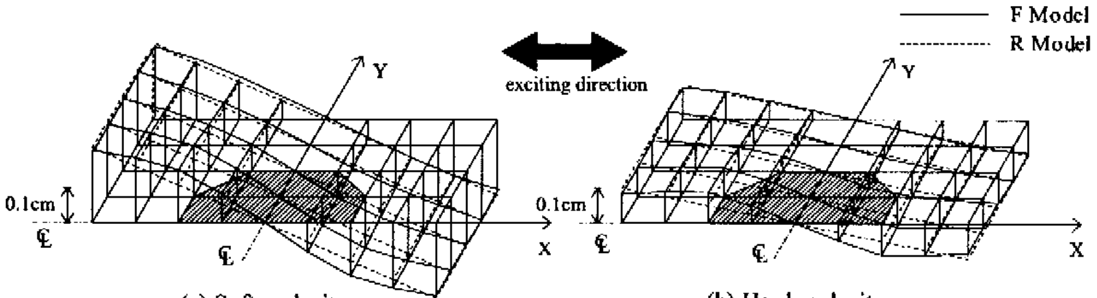
Reference Point (A)



(a) Soft rock site (b) Hard rock site

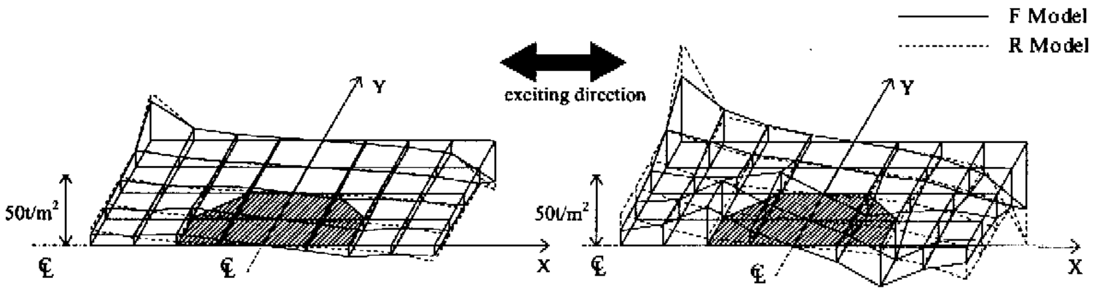
Reference Point (B)

Figure 13: Floor response spectra



(a) Soft rock site (b) Hard rock site

Figure 14: Maximum response vertical displacement of base mat bottom



(a) Soft rock site (b) Hard rock site

Figure 15: Maximum response vertical reaction stress of base mat bottom